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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

Industrial Gears
—the Function of the
Lubricant

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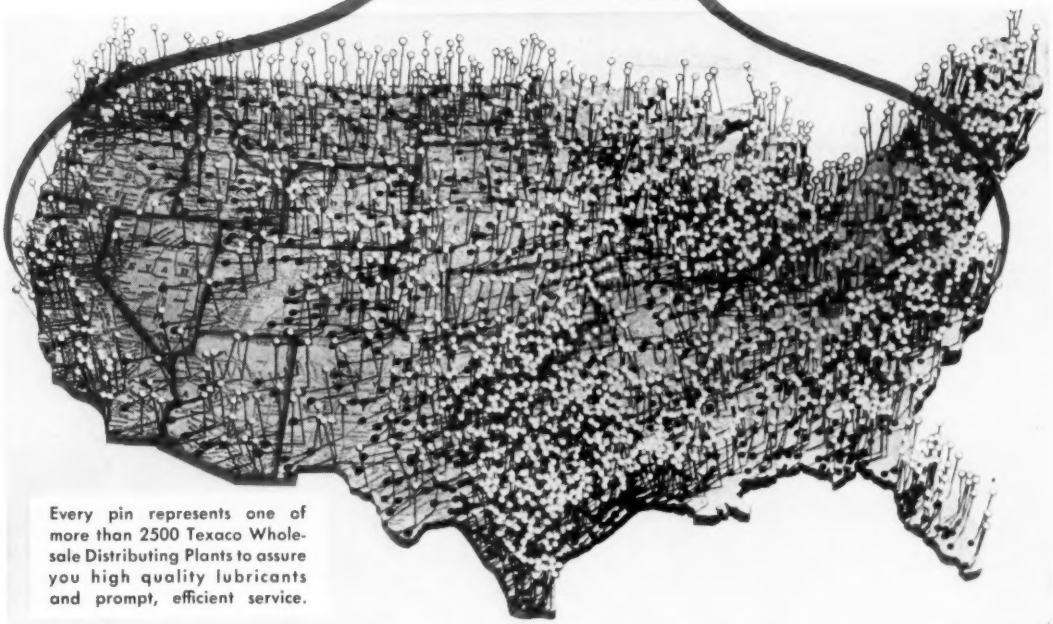

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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Industrial Gears —the Functions of the Lubricant

GEARING — probably one of the oldest mechanisms for transmission of power, is also in its modern form probably one of the most controversial with regard to lubrication. The capacity of metallic gears was made use of by machine designers when the petroleum industry had developed sufficiently to furnish dependable lubricants which would effectually protect gear tooth surfaces from wearing too rapidly. Even from the days of the crude wooden toothed gears it was known that some form of greasy lubricant would prevent noise. Wear was not too serious a factor in those days as speeds were low and gear tooth loads were not excessive; animal fats served the purpose just as they also served to lubricate the bearings of contemporary machinery.

The first petroleum gear lubricants were simply the residual products derived from refining straight mineral oils. They served the purpose very well until the reduction-geared steam turbine was perfected for marine service and more intricate trains of gears were applied to machinery where wide speed reductions were desired. Textile machinery and machine tools were among the first of this type. When automotive engineers designed a truly workable motor vehicle early in the century, gear design really began to progress. The spur gear and straight bevel gear were quite suitable to most of the other types of machines of that period, but the marine steam turbine and motor car required a type of gear which would run quietly at high speeds. The helical, herringbone and spiral bevel ideas served this purpose, the latter paving the way to subsequent development of the hypoid gear.

HISTORICAL DEVELOPMENT

Gear lubricants were widely referred to as compounds for many years even though many types were straight petroleum or mineral oil products. It was a loose application of the word compound for in petroleum parlance compound means a combination of a fixed or fatty oil with a petroleum oil. For the typical spur gear as employed on slow speed steel mill, cement and rubber machinery where rotational speeds do not exceed 100 R.P.M., these heavy bodied straight mineral oils sufficed. More fluid straight mineral oils of turbine grade in turn were better suited to high speed single helical and herringbone reduction gearing where pinion speeds may approach several thousand R.P.M.

At one stage in the early development of gear lubricants the thought prevailed that by thickening a medium viscosity petroleum oil with a material which might or might not have much lubricating value, the latter would take up the shock loads on the gear teeth somewhat like a cushion. Too often these were of doubtful lubricating value since some of them had little ability to re-establish a lubricating film on the tooth surfaces between successive engagements of the teeth. Such a product may stay on the teeth when first applied, but after the teeth have meshed a few times it will either be forced to the base of the space between the teeth where it will probably remain packed, or the action of centrifugal force will cause it to be thrown off.

When this occurs insufficient lubricant usually will remain on the gear tooth surfaces, consequently, boundary lubrication may develop and where pressures are sufficiently high tooth wear will result.

The appearance of the teeth can be deceptive, for even though they may seem to have an oily surface, the film strength is not sufficient to prevent wear. The explanation is that as the teeth become disengaged, the tips, which have been forced down into such a lubricant when meshing tend to wipe over adjacent tooth surfaces and leave an oily appearance although metal abrasion really has already occurred.

FILM-STRENGTH

The necessity for adequate film strength in a gear lubricant became apparent when speeds and tooth loads were increased and when the protective ability of Extreme Pressure lubricants was demonstrated on hypoid gear tooth surfaces. Gear teeth,

Figure 1 — GEAR TOOTH STRESSES

Showing how polarized light photography on photo-elastic specimens indicates stress concentration in meshing gears. The whorls show stress. Note there is more of this stress at square tooth roots of gear at right than on rounded tooth roots of gear at left.

regardless of their design or the accuracy with which they are made, develop a combination of sliding and rolling motion as they pass into and out of mesh. Since sliding always prevails between gear teeth, accompanied so often by very high pressures which are comparable to those encountered in rolling contact bearings, maintenance of the lubricating film is a most important requirement.

In order to understand where film-strength fitted into the program of developing the modern gear lubricants the types of lubrication which can exist must be discussed. They involve:

1 — Thick-film or hydrodynamic lubrication.
2 — Boundary lubrication.

Thick-Film Lubrication

In thick-film lubrication the parts are completely separated by a film of oil so when one tooth surface slides over the other the oil film will be sheared continuously.

The term "film-strength" as applied to thick-film lubrication, therefore, has no significance. The oil film cannot be considered in terms of some material having resistance to puncture or which has tensile strength. It is a fluid material which supports the load entirely by hydraulic action, and the oil characteristic which controls this action is viscosity. As a result, the presence of film strength additives of phosphorus, chlorine or sulfur compounds in the oil can serve no useful purpose in thick film lubrication.

If the viscosity is increased, the oil film becomes thicker and more work is required to turn the gears in and out of mesh. In other words, the friction is increased. However, if the oil viscosity is decreased, the film becomes thinner and although the work required then is less, the high spots on the tooth surfaces approach nearer to each other and the transition from thick-film to boundary lubrication is approached. Similarly, if the load is increased or the speed is decreased, the tooth surfaces approach each other and again the action approaches boundary lubrication.

Boundary Lubrication

When conditions of load, speed and oil viscosity are such that the oil film is too thin to completely separate the gear teeth, then the high spots may begin to touch each other. Thick-film lubrication no longer exists then and the condition is termed boundary lubrication. As the load is increased or the speed is decreased, more and more of the high spots tend to come in contact and the force required to turn the gears increases. Eventually a stage is reached where speed and viscosity do not play a major role, and there is a transition from boundary to thin film lubrication. What actually happens in the very thin film of oil clinging to the high spots and also what happens to the contacting surfaces involves both chemical and physical phenomena.

Research, has shown that certain materials termed oiliness agents are effective in reducing friction under boundary lubrication conditions. These materials are high molecular weight organic compounds containing carbon, hydrogen and oxygen as compared to lubricating oils which contain only carbon and hydrogen. When one end of the lubricant molecule is highly reactive, it has the property

Figure 2 – NORMAL WEAR

This condition refers to the gradual smoothing and polishing of the working surfaces resulting from the sliding and rolling action of the teeth. It is frequently spoken of as "running in". With proper design, manufacture and operation, a condition is reached after which wear practically ceases.

of forming a powerful bond with a steel surface. Then it is called a polar molecule. It is "adsorbed" to the surface so powerfully that the last traces in some cases can only be removed by grinding. A straight mineral lubricating oil molecule has no such effect, although the oxidation of mineral oil in service may form organic acids which are mildly polar.

WEAR – DUE TO WELDING OF HIGH SPOTS

What happens at the surfaces of contacting high spots is interesting. In the case of steel on steel, the lubricant present, even the adsorbed polar molecules, cannot always prevent minute high spots from deforming and breaking off to form fresh surfaces of clean metal. When two freshly formed surfaces slide over each other the local temperature at these spots becomes very high because a considerable amount of heat must be dissipated over a very small area. As a result, welding takes place, and the rupture of the metal to form more fresh surfaces occurs. If conditions are right, more and more metal is torn off. By this time most of the prominent high spots have been removed and instead of welding of the small peaks of a few high spots, larger areas weld, thus leading to gross removal of metal. This is aggravated as the speed and load is increased. Research has demonstrated that with the higher loads the maximum localized temperature is reached at a lower speed, and conversely at a high speed, the load required to reach maximum high spot temperature is lower than at slow speeds.

This explains why lubricants that are satisfactory for spiral bevel gears may not have sufficient Extreme Pressure characteristics for hypoids. The sliding action is more severe in hypoid gears, so consequently, for the same load, the contacting high spots of hypoid gears are more likely to reach welding temperatures.

WHY AND HOW GEARS FAIL

When a gear tooth fails it may involve actual breakage of one or more of the teeth, or there may be failure of the tooth surfaces. Tooth breakage is rarely attributable to faulty lubrication. Poor metal structure, faulty design, abuse or excessive overloading are more usually the cause. Lubricants which would otherwise be amply protective cannot insure against failure under such conditions, nor can they always keep the temperatures within reasonable limits. Abnormal temperatures from any source whatsoever, can cause imperfect surface lubrication with resulting excessive friction. Then scoring and/or scuffing may develop, along with perhaps softening and cracking. Under such conditions the temperature over the contact areas of the teeth has probably become high enough to reduce the viscosity of the oil film to such an extent that the lubricating value of the film on the teeth is negligible. If this continues, more friction, more heat, less lubrication and more tooth failures will result.

On exposed gears, the lubricant must be adhesive as well as viscous – otherwise the film cannot resist the action of centrifugal force. There is no continuous replenishment of lubricant on the surface by dip or spray as is possible with enclosed gears.

Where dealing with bath or dip lubricated gears, the lubricant is chosen so that at the operating temperature the viscosity will be sufficient to train with the teeth. If the oil is too light an insufficient amount may be carried by the dipping gear to the companion gear or worm. In this case, the cooling ability of the lubricant will be lost. Under such conditions, a worm gear for example, may run so hot as to cause the threads to soften and crack, or to result in wiping of the bronze teeth of the worm

Figure 3 – INITIAL PITTING

This term applies to the formation of small *pits* in the tooth surfaces, as large as the head of a pin or smaller, usually starting in the vicinity of the pitch line, and frequently occurring during the initial period of gear operation. *Pitting* should not be considered as detrimental, unless it advances beyond the *initial* stage. If *pits* occur gradually, and do not increase rapidly, they indicate a temporary condition and may disappear entirely in the course of normal wear.

Figure 4 — PROGRESSIVE PITTING

This type of failure is indicated when the formation of *pits* continues at an increasing rate, both as to number and size. A point may be reached when the unpitted areas of the tooth surfaces are insufficient to carry the load, and complete destruction of the tooth shape may occur, especially after continued operation at relatively high load, and over loading.

wheel. For this reason, some designers improve the adhesiveness of a worm gear oil by using a compounded product containing an oiliness agent. Other authorities feel that a lubricant containing lead napthenate (which has mild E.P. properties) and which is non-corrosive to copper, bronze or steel, provides an added factor of safety. In a worm gear the rate of sliding is greater than in a spur, bevel or helical gear.

SURFACE FAILURE

Wear

When the tooth surface of a gear becomes impaired, it may progress through several accepted states. First, more or less abrasion or rubbing off of the metallic surfaces occurs. Spur, helical or bevel gears will often become smooth and highly polished during the initial stages of abrasive wear. To some extent this could be regarded as a "wearing-in" procedure. It is regarded as being related to the viscosity of the gear oil, as it is apt to occur more rapidly with lower viscosity lubricants. A heavier oil or one with E.P. characteristics will present a more durable film on the teeth and retard this type of wear. High tooth loads and low speeds also contribute if the viscosity of the oil is not chosen accordingly. Evidence of wear is most pronounced below the pitch line of the pinion if lubrication has been ineffectual. While abrasive wear is progressing the theory is that the fine metallic particles which are worn off the teeth, mix intimately with the oil film to develop a lapping action.

Scoring and Galling

These often follow abrasive wear due to actual metal-to-metal contact. Here wear is more severe and tearing of the tooth surfaces is evidenced. Normally this occurs in the direction of sliding. Scoring develops regardless of the hardness of the tooth surfaces, but it often may show more of a tearing nature and develop into galling with softer surfaces where total absence of any oil film has permitted welding to occur between the high spots of the tooth surfaces.

The E.P. Theory

The theory back of this welding action, which, incidentally, led to the development of Extreme Pressure gear oils, is of interest. Research has indicated that so long as the high spots on the teeth are at all times separated by several molecular layers of oil there can be no wear of the type known as abrasion or scoring. If the mechanical attack at the contact areas of metals rubbing together becomes severe enough to remove the ultimate protecting film, the clean metals will seize, possibly causing irreparable damage to the surfaces. This seizure, which is welding on a small scale, can become progressive to result in the gross removal of metal, i.e., tearing. In other words, the volume or thickness of the oil film under the prevailing pressure and sliding velocity determines whether or not an E.P. lubricant is necessary. When boundary lubrication conditions are involved the use of an Extreme Pressure oil should be seriously considered. Beyond boundary lubrication it is absolutely necessary to counteract the shock or intermittent loads which develop at high speeds. The theory is that Extreme Pressure additives cause the oil molecules to adhere strongly to the tooth surfaces either chemically or by polarity.

One of the most difficult problems of lubrication which has developed in recent years is in connection with hypoid gears. Intensity of load and speed of rubbing are such that a special lubricant is re-

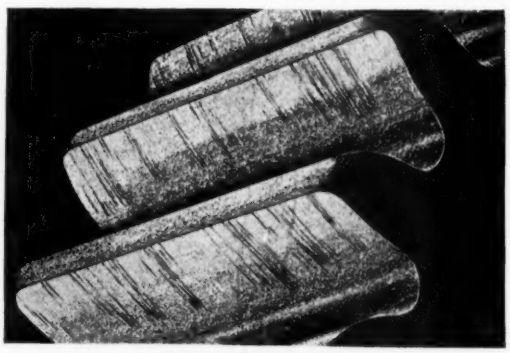


Figure 5 — ABRASION

This condition may be described as a general wearing away of the tooth surface at a comparatively rapid rate. It generally results from the presence of foreign matter such as dirt, grit, or metallic particles in the lubricant. It may also be caused by a breaking down of the material on the tooth surfaces, as for instance in cast iron gears. *Abrasion* appears as fine scratch marks up and down the tooth profiles closely distributed over the surfaces. Lack of proper lubrication may result in *abrasion*.

quired. Wherever high power losses and wear prevail there is a problem. Under high loading the oil film between the high spots becomes extremely thin. So long as it exists at all there can be no clean metal contact, and therefore no abrasion, but this condition can only continue so long as the rate of removal of the film does not exceed its rate of renewal. Industrial gearing need not be of the hypoid type to require an E.P. lubricant; loading is a factor.

In industry, where gearing is adequately proportioned in line with A.G.M.A.* practice, and housed, comparatively fluid lubricants are generally applicable. They are applied to the gear teeth and bearings either by force feed lubrication or splash in contrast to automotive service where bath lubrication prevails.

Pitting

Pitting involves the formation of small pits in the tooth surfaces, usually starting in the vicinity of the pitch line, and frequently occurring during the initial period of gear operation.

Pitting is related to surface cracking; it is a fatigue failure. It involves actual removal of surface material to a depth dependent upon the localization of stress. While it occurs very often at low speeds and at low operating temperatures where high torque prevails it is not restricted to low speed.

Where constant repetitive shock loading or hammer action is induced by some action in the machine, a condition akin to fretting corrosion occurs which can cause the teeth to pit.

*A.G.M.A.—American Gear Manufacturer's Association

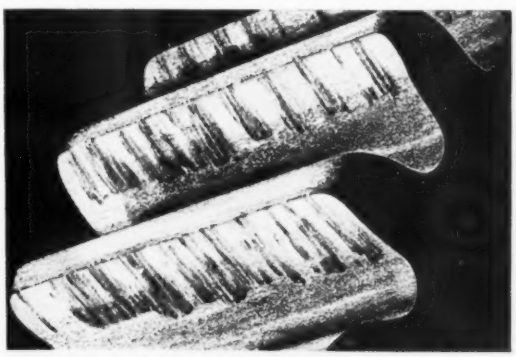


Figure 6 — SCORING

This condition results from excessive loading or inadequate lubrication. *Scoring* may occur even in gears which have been properly designed, manufactured and installed, when conditions of operation are such as to cause metal-to-metal contact. The tooth surfaces may be roughened only on small areas and on the same position on all teeth. This may be followed by a general disintegration of the surfaces, if abnormal conditions of operation are continued. *Scoring* in its initial stages may sometimes be eliminated by applying more effective lubrication, such as the substitution of a general purpose E.P. lubricant.

Figure 7 — GALLING

***Galling* is an aggravated condition of scoring caused by particles of metal torn out from the tooth surfaces in a manner that is sometimes referred to as *seizing* and *welding*. This condition is more likely to occur when two comparatively soft gears of the same hardness are operated together under heavy load conditions.**

The Problem Often Solves Itself

Fortunately, actual failure of gear teeth seldom occurs. Wear, scoring, incipient pitting and other conditions — may develop, as already stated, but they usually can be arrested by proper preventive measures with the result that the gear assembly in question will run successfully for years thereafter. Some authorities feel that at least minor wear is essential to the running-in process whereby local high spots on the tooth surfaces are worn down. While this is going on, localized stresses may be developed which will generally cause some pitting, entirely unrelated to the lubricant used. Partial proof of the assumption that this pitting often corrects itself has been evidenced where the pitting has been cleared by continued abrasion until relatively smooth and satisfactory mating surfaces have developed on the teeth. Some tooth surface deformations may still be evident, but normally a satisfactory polish is acquired which is indicative of even distribution of the load and satisfactory lubrication.

SELECTING GEAR LUBRICANTS

Lubrication engineers are handicapped when it comes to scientific methods for selecting gear lubricants. They have had to rely on accumulated experience. There are no generally accepted formulae as have been developed by students of bearing lubrication for plain bearing applications. It is easy to understand this because even though the interest in gear lubrication has been equally as active as that shown in bearing problems, the conditions involved in gear lubrication are far more complex. The design of full scale test equipment is equally complex. Laboratory testing procedures, so far, have not resulted in sufficient data which could be used to establish the relation of optimum oil viscosity to gear design, tooth loads, speed, operating temperatures and methods of lubrication where thick film

Figure 8 — BURNING

This condition is indicated by discoloration of the tooth surfaces of the type associated with high temperatures. Such discoloration indicates that excessively high temperature has actually occurred, and may be caused by overspeed, overload or faulty lubrication. Burning may result in a reduction in the hardness of hardened steel gear teeth and worm threads, making them unsuited for carrying the specified load.

lubrication is involved. On the other hand there are several devices for studying thin film or Extreme Pressure conditions, for example the Almen, Timken, S.A.E., Falex and Four Ball machines. While these machines have been very useful in controlling quality and uniformity, the data derived are not necessarily related to specific gear performance, which limits their value in the selection of a lubricant for a specific application.

A comparison of interface action in these testing machines with the action at contacting gear faces indicates that these machines do not duplicate the conditions at the tooth surfaces of mating gears. The principal points of difference are, that the tests involve a continuous constant velocity rubbing action which, in all but the S.A.E. machine, occurs without relief on a single spot of one of the contacting surfaces, whereas, actual gear tooth faces come into and then go out of contact, with a slide-roll-slide action, which means that individual surfaces have a period of relief between successive contacts.

Specimen failures in these test machines occur in ways that are characteristically different from failures in real gears. In each case, the failures are produced within very short time periods. They generally are the result of welding or severe galling of the contacting surfaces and are usually accompanied by extreme heating which, on occasions, is sufficient to discolor and deform the specimens. In actual gears, the failures occur over much greater time periods such that they assume something of the nature of fatigue phenomena. Furthermore, gear tooth failures are characterized by pitting (surface fatigue) and wear, which, when it is fairly rapid, has the appearance of welding between local portions of the mating tooth surfaces, being called spalling, galling, gouging, etc., depending on its extent and appearance.

A further point of difference is that the aforesaid test machines are more or less limited in specimen materials to some specific steel treatment and finish which is not truly representative of gear practice.

The Service Problem

Apart from what current research programs may prove or develop in the form of speed-temperature-load relationships to oil viscosity for various types of gears, experience has proved that certain definite physical or economic properties must be related to a gear lubricant if it is to be satisfactory in service.

The prosaic method of "cut and try" indicates that according to the type of installation, it must:

1—Be adhesive (when used on exposed gears) to insure that a film remains on the teeth regardless of the action of centrifugal force.

2—Be of adequate viscosity so as to resist the effects of heat, and maintain a suitable film, regardless of tooth pressures or temperatures.

3—Show no tendency to channel, harden or become brittle and chip off in case of exposure to abnormally low temperatures.

4—Have sufficient "oiliness" or lubricating ability to reduce to a minimum the friction which occurs between the teeth under boundary conditions.

5—Be economical, so that it can be purchased and applied at a reasonable expenditure in comparison with the value of the service rendered.

6—Possess Extreme Pressure quality for hypoid gearing or heavy-load service.

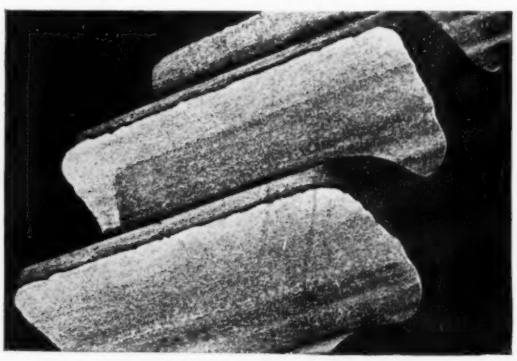


Figure 9 — ROLLING and PEENING

These terms refer to a plastic flow of the tooth surfaces, which may occur when the material in the gears is ductile in compression, and of insufficient hardness. *Scoring* may or may not be present. One effect of rolling is the formation of slight "fins" at the top edges and ends of the teeth. Rolling refers to that condition where plastic flow takes place due to heavy continuous loading; *Peening* where the load is intermittent resulting in a plastic flow of the material due to "hammer blows".

Tooth Pressures

Unit tooth pressures are high in the average gear installation, inasmuch as a relatively small area of contact is involved. Were rolling contact alone involved, the intensity of such a load momentarily on any part of a gear tooth could be disregarded as far as wear is concerned. But as sliding motion is involved most of the time this explains the abnormal wear that occurs even under normal loads where gears are not properly lubricated, or, in other words, where the tooth surfaces are subjected to a continual lapping action.

Nature of the Lubricant

All this time gears have had to be lubricated, even though there was no scientific procedure for ascertaining the most suitable viscosity for any or all cases. Practical experience over the years resulted in the development of a considerable variety of gear lubricants to meet the requirements stated above. Today they vary all the way from fluid mineral oils to intricate compounds. Any material which serves only as a thickener and has little or no lubricating value is not recommended for modern gearing. It may very well be deceiving in that an uninformed user may believe that his lubricant is suitable, when, in reality, it is giving comparatively poor protection against wear. The necessary adhesive characteristics may also be relatively low. As a result, when used under high-speed conditions, or wherever the gears may come into contact with water, acids, alkalis, or chemical fumes, the gear teeth may lose their protective film of lubricant, due either to its being thrown off by centrifugal force, or washed from the wearing surfaces.

Figure 10 — CRACKING and CHECKING

Cracking refers to the occurrence of single or scattered cracks in the tooth surface which do not necessarily result in failure.

Checking refers to the formation of numerous and closely grouped cracks in the surface.

Cracking may result from loading and lubricating conditions causing excessive temperature fluctuations; and also from excessive hardness. *Checking* may result from several causes. The direction and arrangement of the *cracks* and *checks* usually indicate the probable causes. Frequently, *cracks* and *checks* can only be detected by etching or by the "magnaflux method". For cracks in fatigue failures, see *fatigue breakage*.

Figure 11 — CHIPPING

This term refers to the breaking off of portions of material at the edges or boundaries of the teeth. It may indiate excessive brittleness, when it occurs under normal load. Another term indicating this condition is *spalling*.

The lubricating film developed upon the gear teeth must be able to resist the squeezing-out action which is developed. The tips of the teeth often exert a so-called "smearing" action on the sides of the adjacent teeth when rolling out of mesh, picking up a certain amount of lubricant which has been forced down between them. If the lubricant is unsuitable the teeth may appear to be carrying a sufficient amount, yet this will be present only after the pressure between teeth has been relieved. As soon as adjacent teeth engage, metal-to-metal contact may take place with resultant wear and abrasion, due to this type of lubricant being unable to withstand the pressure. Oftentimes, this can be proven by the presence of metallic particles when the used lubricant is subjected to laboratory analysis. Load carrying ability is most effectually obtained by using a lead-naphthenate compound which imparts mild extreme pressure characteristics to the lubricant.

CONDITIONS OF OPERATION

Gear lubricants may be exposed to adverse operating conditions, according to the extent to which the gears are housed.

The presence of considerable dust in the air as a result of material used, as in the cement, steel or rubber industries, may cause heavier gear lubricants to become veritable lapping compounds. Any type of dust is more or less abrasive; if it cannot be kept from contaminating a gear lubricant, the viscosity of the latter should be reduced in order to increase the washing action. Increasing the flow of lubricant over the gear teeth is also recommended.

The heavy pressures that are customary on certain types of steel mill pinions, rubber plant mixers, or cement mill kilns, may squeeze out ordinary lubricants, permitting actual tooth contact. Under these conditions E.P. qualities such as possessed

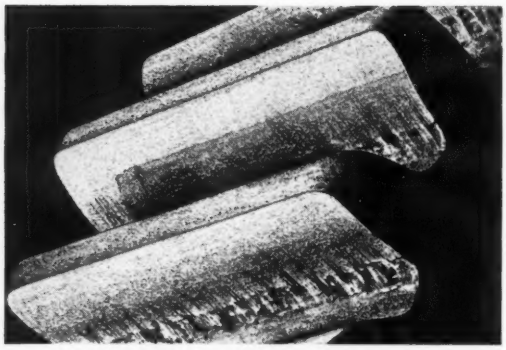


Figure 12 – GOUGING

This may occur in unhardened gears when there is interference between the flank of the driving pinion and the tip of the driven gear. The top edges of the gear teeth may gouge the material near the roots of the pinion teeth. A similar effect may occur between the edge of a hardened worm thread and the teeth of a worm gear.

by lead naphthenate lubricants are desirable. The theory of Extreme Pressure additives already has been mentioned. The modern E.P. gear oils have been a valuable contribution to industries where increasingly heavier gear tooth loads must be encountered, and yet the gears cannot be fully protected against lubricant contamination. The increased load-carrying ability of these oils permits the use of far more fluid products than was possible when only straight mineral gear lubricants were available.

Power transmission gears must never run dry, nor, in turn, should they be over-lubricated; this latter can cause churning losses and increase the difficulty in retaining the lubricant. According to the type of service experience has, to date, dictated approximately the proper viscosity, just as it has promoted suitable methods of application. Where gears are enclosed in cases which permit of pressure splash or dip lubrication, the lubricant should be maintained at the level recommended by the manufacturer. Very often, the latter also recommends draining periods and rate of make-up.

Where heavy bearing pressures prevail, these, in turn, may be transmitted to the gear teeth to some extent. Sometimes adjusting screws are employed to regulate the pressure to suit the work; widely varying duty may, therefore, be demanded of the reduction and driving gears. Where slower speeds are customary, the possibility of overheating or throwing of the lubricant is reduced; yet wear may be appreciable if a proper film does not coat the teeth completely.

To further appreciate the extent to which such conditions may affect the performance of a gear lubricant, it is interesting to note the several successive reactions to which the latter will be subjected. There are three distinct phases involved, viz.:

1. When the point of the gear tooth comes into contact with the root of the companion pinion tooth.
2. Where both teeth are in contact adjacent to their pitch lines.
3. Where the reverse of the first takes place as the teeth pass out of mesh.

Sliding motion occurs most actively when the teeth first come into contact and as they become disengaged, the points of the respective elements developing a certain amount of scraping action on the sides of the adjacent teeth. Both wiping action and squeezing will be apt to occur at these times. As the teeth become more and more engaged however, rolling contact becomes more pronounced. Wiping or scraping off of the lubricant is less apt to occur under these conditions, but the squeezing out action still is possible, especially as maximum contact pressures are encountered during the time the teeth are so engaged. Wear will occur more rapidly at the points and roots of the teeth due to the sliding friction involved; whereas, the intermediate tooth surfaces adjacent to the pitch line being subjected to rolling action will resist wear more effectively.

METHODS OF GEAR LUBRICATION

The service involved dictates how a gear lubricant should be applied. Everybody is familiar with automotive practice where the gears in the transmission and rear end are bath lubricated. Contrast this with industrial production: for example, the gears which drive the rolls on certain rubber machines, which may be either bath or hand lubricated; the gearing on excavating machinery which is largely hand oiled; and turbine reduction gears which are lubricated by force-feed. This latter method of lubrication is also now widely applied to enclosed type steel mill reduction gear sets, and a

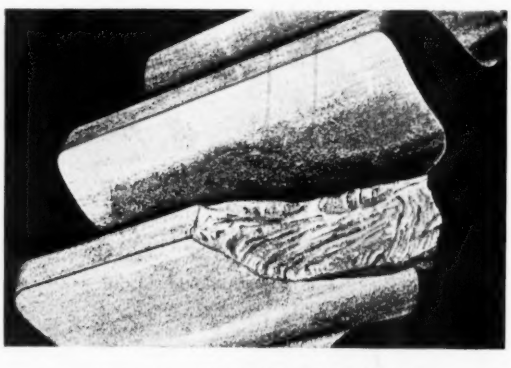


Figure 13 – OVERLOAD and BREAKAGE

This term refers to gear tooth breakage caused directly by an unexpected shock or overload – due for instance to the jamming of other machinery – of a nature which cannot be attributed to improper design or faulty manufacture.

considerable variety of other heavy duty production machinery.

The lubrication engineer must consider each installation according to the design of the machine, the size and number of gears and the products being handled. Certain of the latter will be of a perishable nature, such as foodstuffs, paper and textiles. Gearing on such machinery must be so lubricated that there will be practically no chance of the gear lubricant splashing, dripping or being thrown onto the products being handled. Contamination of the product is not a serious factor in heavy industry machine lubrication where the gears are enclosed; here load conditions are more important.

Gear installations can be grouped into five classifications according to their housings, or lack of housing, i.e.;

1. Those which are enclosed in a suitable housing, out of contact with the bearing lubricant, running either in a bath of oil or being pressure lubricated.
2. Those which run in an enclosed case, the gear lubricant at the same time serving the gear shaft bearings.
3. Those which are entirely exposed, the gear lubricant being manually applied by pouring or swabbing.
4. Those which are exposed, but run with their lower teeth encased to permit bath lubrication.

Figure 14 — FATIGUE and BREAKAGE

This term refers to tooth breakage as a result of repeated loading, and is usually characterized by the formation of cracks at highly stressed locations, which progressively extend in area and depth until failure occurs. *Fatigue breakage* is not necessarily an indication of poor design or faulty manufacture. It merely means breakage after a large number of repetitions of load, as distinguished from overload breakage, which may be the result of a single application, or a comparatively few applications of excessive load. In fact, it is the practice in automotive and aircraft design to proportion the gears, so that they will fail by *fatigue* after they have fulfilled their rated length of service. It is usually possible to ascertain from the character of the surfaces of the fracture, if the failure is from fatigue.

Figure 15 — FRETTING CORROSION

Showing how fretting corrosion occurs on aircraft gears as a result of high frequency vibration under high load.

5. Those which operate exposed to such dirty conditions that protective lubrication is very hard to attain.

Review of these conditions indicates why it is so often a problem to decide where and when to use any specific grade of gear lubricant. It is disconcerting to the plant engineer to have a highly efficient assembly of machinery with the exception of a noisy set of gears which may refuse to "settle down" under ordinary methods of lubrication. Today however, this problem is not entirely hopeless, even though perhaps the air may be filled with dust, or the gears subjected to hot water or acids, etc.

There is available a wide variety of specialized lubricants which are manufactured so as to be readily applied at low temperatures, reverting by evaporation to the desired viscosity in service; others will stick and lubricate even when totally submerged in practically boiling water; still others will withstand wide ranges in tooth loading. These special products along with the wide range of straight mineral oils which are suitable for many types of gear service will serve virtually any condition of operation or means of application. When the lubrication engineer has available more precise means of determining the best viscosity to use, gear lubrication problems should be reduced.

In Exposed Service

Gear lubricants must be protected against contamination in service whenever possible. Where pans are furnished for bath lubrication these should be cleaned out at regular intervals, since any dust that may have gained entry will impair the ad-

hesiveness and affect the lubricating ability of the gear lubricant. The resultant solid pasty mass cannot be picked up readily by the gear teeth. Gears which dip in a bath of lubricant require a bath just deep enough so that the lowest teeth are just covered. This will give ample lubrication and keep the consumption of the lubricant at a minimum.

Gear lubricants designed for application by hand usually are so heavy in body as to require heating to reduce them to the consistency desired. They are applied hot by brushing or spraying or pouring onto the teeth as the gears are slowly revolved towards each other. Pouring the lubricant on in a fine stream is easy, economical and effectual.

Lubricants should be applied to open gearing relatively frequently and in small quantities, rather than in considerable volume and at longer intervals. Thus there will be less danger of gobs of lubricant being thrown off by centrifugal force, to possibly contaminate the products passing through the machine.

Should the lubricant become laden with foreign material and build up at the roots of the gear teeth or between the gear and its housing, the deposits usually can be softened by kerosine or some petroleum solvent to facilitate subsequent removal. As these materials are inflammable they should not be used on gears in confined or poorly ventilated locations where an open flame might cause an explosion of the vapors. Non-inflammable solvents should be used in such instances.

WORM GEAR LUBRICATION

Lubrication of worm reduction gears (bronze to steel) has been the subject of considerable study during recent years. There has been a definite trend away from the time-honored compounded steam cylinder oil as a general recommendation for such gears in severe service. Modern, lubricants compounded with lead soap and sulfurized oils which are non-corrosive and have excellent stability even at high operating temperatures, are receiving more and more favor. For marine service the rust and oxidation inhibited turbine grade mineral oils are well suited for high speed pump drives as well as other engine room machinery where it is desirable to stock as few lubricants as possible. Both the above types of lubricants have the advantage of protection against rusting when water may be present.

Worm gears are distinctive in that their design and method of housing enable the use of comparatively fluid lubricants. Worm gears are rarely exposed so automatic lubrication activated by the meshing of the gears themselves is practicable, involving an oil bath or specially designed oil circulating system.

How the Mechanism Works

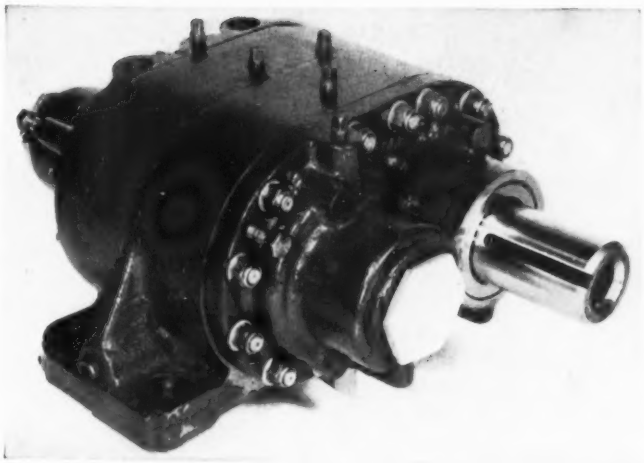
Worm reduction gears are applicable where motion is to be transmitted between two non-intersecting shafts, located in different planes at right angles to each other. The worm, which is usually the driving element, is a cylinder, on the surface of which is cut one or more continuous helical teeth, which more or less extend round and round over the entire length. Its companion mechanism is a helical type of gear usually made of phosphor bronze. Worm gears are well suited to conditions requiring a comparatively high reduction ratio with a minimum of gears.

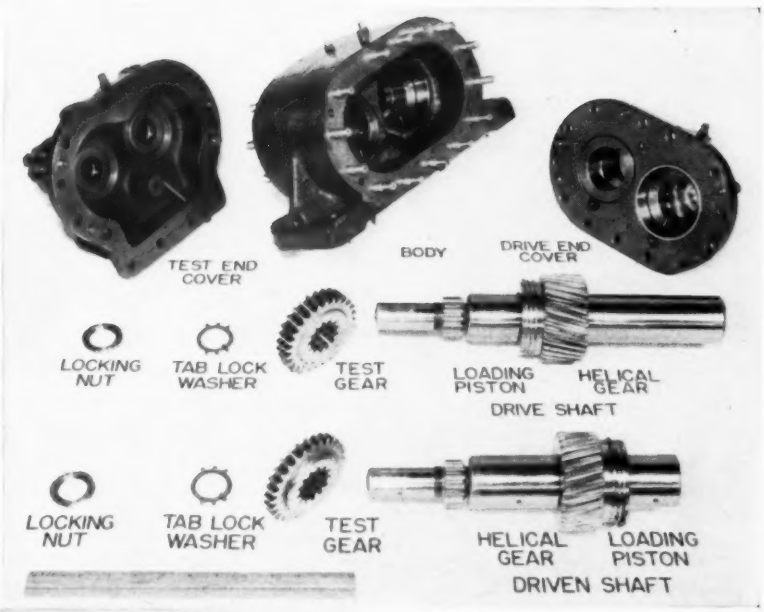
Tooth friction will depend to a considerable extent upon the suitability of the materials used, the alignment of the gears, the accuracy of their cutting and the freedom with which their teeth engage or mesh, as well as the condition of the bearings. Under ideal conditions, the teeth should slide so smoothly into each other and with such a constant relation in velocity between their respective surfaces that this friction will be reduced to a minimum. A suitable lubricant will play an important part in reducing noise and frictional heat, preventing wear and eliminating vibration or chattering between the teeth.

Factors Governing Lubrication

For lubrication to be effective an ample film of lubricant must be kept on the worm and gear teeth to prevent wear, to reduce the starting and operating torque as far as possible and to lubricate the shaft bearings with a minimum of frictional resistance. Ball and roller bearings are extensively used in such installations, especially for the worm shaft, and for the purpose of taking up end-thrust. In theory, anti-friction bearings should be served with as low a viscosity lubricant as will provide effective lubrication, protect the highly polished surfaces and serve as a coolant. A compromise may often be necessary, especially when the one lubricant must be used throughout the gear set and protection of the bearings is as important as protection of the gears.

Where worm gears are bath lubricated the level of the oil is of decided importance, for the development of "drag" or excessive internal friction may have an appreciable effect upon power consumption. As a rule the oil should be carried at such a height as to insure suitable dipping of the teeth of the lower element; submergence of too much of either the gear or worm is not advisable. Usually provision will be made for distribution of the lubricant by the teeth of the gear to the respective shaft and thrust bearings, or else there will be means for external or independent lubrication. Where the worm is located below the wheel or gear, the oil level should usually be carried at the center-line of the worm shaft. Where the worm is above the





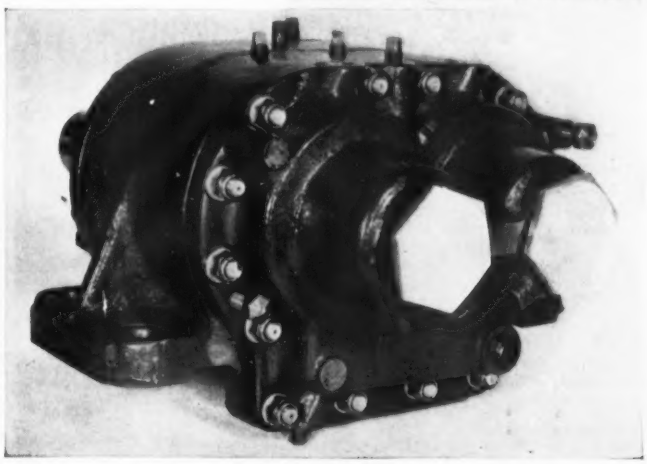


Figure 16

Top — Drive end of the modified Ryder (Pratt & Whitney) gear and lubricant test machine.

Center — Disassembled view of the parts of this machine.

Bottom — Test end of the same machine.

gear, however, the problem may be more difficult, for the gear teeth will carry less lubricant to the worm than this latter would to the gear teeth. So a heavier, more adhesive lubricant may often be necessary, or the level of the lubricant may have to be raised considerably higher than for normal spur gear requirements.

Selection of Worm Gear Lubricants

Modern design dictates that a worm gear lubricant must have certain definite properties in order to function effectively, i.e.

1. The lubricating ability or "oiliness" must be adequate to insure the reduction of both solid and fluid friction to a minimum.
2. The viscosity or body must be suited to the method of lubrication and the amount of heat that may be encountered so that a suitable film will be insured between the teeth to withstand the effects of both pressure and temperature. Pressure exerts a squeezing out action; elevating the temperature causes a lubricant to become more fluid, according to its degree, for viscosity is reduced as temperature rises.

Pressure is of distinct importance in the study of worm gear lubrication. Tooth pressures normally will be high and the bearing surfaces, due to their relatively small areas of contact, will carry heavy loads.

Inasmuch as contact between a new worm and gear set is not as perfect at the start as it becomes after the worm has seated itself in the gear, the unit pressure between any two such elements will normally be greatest during the "wear-in" period. Unit pressure becomes minimum and constant after seating is completed. It will require some time for the wearing-in process of a worm and gear to become complete, depending upon the ratio and imposed load.

When excessive wear occurs particles of bronze are worn from the gear and may adhere to the worm, in the zone of contact. The resultant comparatively rough surface will tend to score the gear and cause continuation of wear. If this can be caught in time further wear can be prevented by removing the worm and cleaning all traces of bronze from the worm threads.

Under conditions of this sort the non-corrosive type of lead soap gear oil should give protection against further excessive wear.

Application

Where the gear set is designed so that the same lubricant serves both gears and bearings the lubricant must be sufficiently fluid to follow the bearing clearances and yet viscous and adhesive enough to maintain a satisfactory film on the gear teeth.

The use of anti-friction bearings frequently presents another problem, wherever they are contained within the case, for their protection is as important as the lubrication of the gear teeth and the reduction of starting and running torques.

This has developed another point for discussion when non-corrosive lead soap lubricants are considered. Evidence accumulated in actual service has proved that the mild, E.P. non-corrosive lead soap gear lubricant has a definite place in worm gear lubrication whenever severe duty prevails. It is also valuable in protecting the worm and gear tooth surfaces from wear, corrosion and rusting under heavy duty conditions and has no detrimental effect on the anti-friction bearings if kept clean so there is no sludge and consequent abrasive wear of bearing. The oil film is unusually persistent, resisting displacement by the shearing action of the sliding teeth. The resultant decrease in frictional heat gives added protection from fatigue pitting of the bronze and steel tooth surfaces. Also unusual protection from rusting of gears, gear case and bearings is afforded since the oil film resists displacement by water to a remarkable degree.

CONCLUSION

In a later article it is planned to supplement with new data this article and previous articles on the same subject* which have appeared in "Lubrication" during recent years. The photos shown in Figure 16 give an idea as to the nature of the test machines which are being used. The objective is to test gear lubricants in the laboratory under conditions which will be akin to those the lubrication engineer encounters in service. This research is aimed at the development of formulae which will enable gear lubricants to be selected more precisely as to viscosity and other properties related to performance in modern gearing. The program will allow proper consideration to be given to gear design, gear operation and gear lubrication in order to obtain the best results from modern industrial gears using modern industrial lubricants. The operator should not find it necessary to resort to specialty lubricants to compensate for faulty construction or design deficiency.

*Industrial Gears—Designing for Lubrication—Sept., 1945
Automotive Gears—June, 1944

Figures 2 through 14 with terms and definitions used in designating gear tooth wear and failure are reproduced by courtesy of American Gear Manufacturers Association from A. G. M. A. Tentative Standard Nomenclature.

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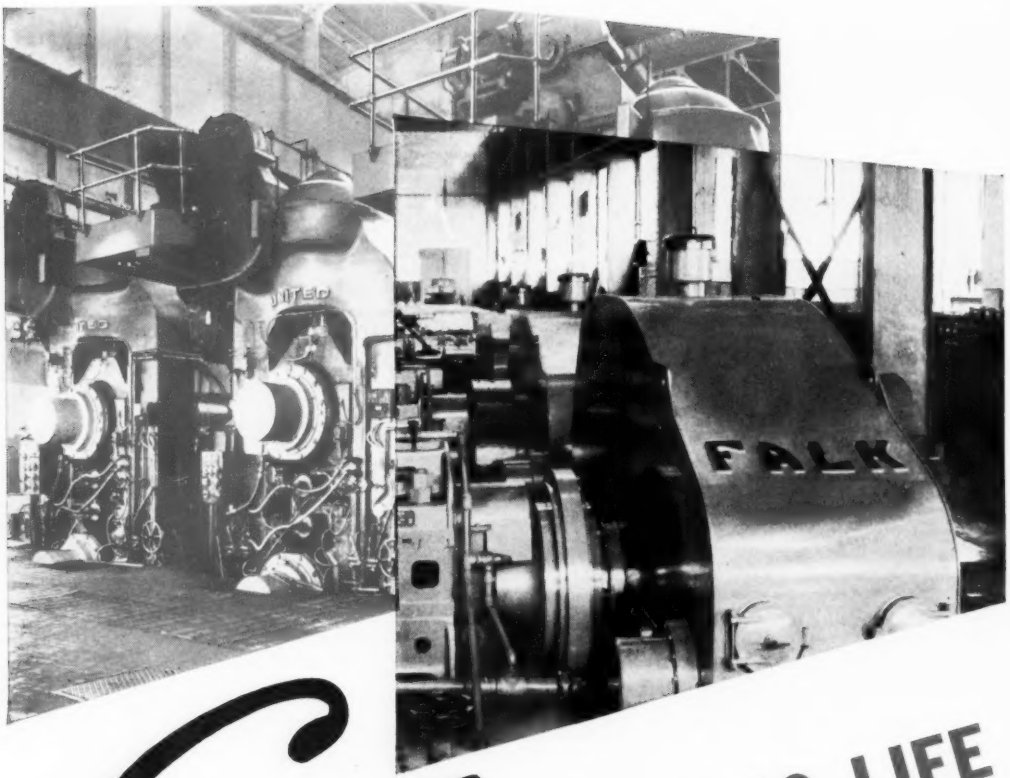

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